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Helium Pot System for Maintaining Sample Temperature after Cryocooler Deactivation

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ABSTRACT

A system for maintaining a sample at constant temperature below 10 K after stopping the cooling source is demonstrated. In this system, the cooling source is a 4 K GM cryocooler that is joined with the sample through an extension that consists of a helium pot and a resistive medium. Upon deactivating the cryocooler, the power applied to a heater located on the sample side of the resistive medium is decreased gradually to maintain an appropriate temperature rise across the resistive medium as the helium pot warms. The sample temperature is held constant in this manner without the use of solid or liquid cryogens and without mechanically disconnecting the sample from the cooler.

Shutting off the cryocooler significantly reduces sample motion that results from vibration and expansion/contraction of the cold head housing. The reduction in motion permits certain procedures that are very sensitive to sample position stability, but are performed with limited duration.

A proof-of-concept system was built with an extension 67 mm in diameter and 282 mm in length that includes a helium pot pressurized to the cryocooler's charge pressure. A sample with continuous heat dissipation of 100 mW is maintained at 7 K with a cryocooler duty cycle of 20 minutes on and 13 minutes off.

INTRODUCTION

Cryocooler systems can offer simpler operation in comparison to liquid helium systems for cooling below 10K. However, common off-the-shelf systems, such as Gifford-McMahon (GM) and Pulse Tube (PT), inevitably impart motion to the cold sample. Sources of motion from cryocooler systems can include (1) cyclical displacement of the cold sample mount, (2) vibration propagating from the cold-head's room-temperature mount, (3) vibration of the helium compressor, and (4) motion of the gas lines that connect to the cold head. The GM systems produce all four disturbances. The PT system is shown to produce significantly less vibration at the cold-head's room-temperature mount, but still exhibits significant motion at the cold sample mount[1]. The compressor and gas lines may also be significant with PT coolers.

In certain applications, such as characterization of inertial confinement fusion (ICF) targets using x-ray phase contrast imaging [2], sample position stability must be on the order of 1 micron or less. The use of a common cryocooler that operates continuously in such applications implies increased design effort and system complexity to isolate the cryocooler's mechanical disturbances from the sample and perhaps other equipment. There are some extremely low-vibration alternatives to GM and PT coolers, such as Joule-Thompson systems or reverse Turbo-Brayton cycles, but these are very costly to develop.

Alternatively, if sub-micron position stability is only required during brief operations such as a measurement which requires only several minutes to complete, then intermittent operation of the cryocooler system may be possible. The cryocooler is shut-off just before the measurement and restarted at its completion. This option is certainly less expensive and less complex than development of a custom cryocooler, or a vibration mitigation scheme to be used with an off-the-shelf system. But temperature stability now becomes an issue. The sample will begin to warm as soon as the cryocooler is stopped. There is a limited acceptable temperature range for every application; if the range is narrow then the hold time during which the cryocooler can be stopped is brief.

The addition of material to slow the temperature rise, either by utilizing heat capacity or latent heat of phase change, will extend the hold time. Such a scheme has been previously proposed for superconducting magnet systems operating in the range of 8—10 K[3]. This scheme requires the addition of a room-temperature gas, such as nitrogen, that is solidified and maintained in thermal communication with the cold sample. The heat capacity of the solidified gas slows the warming of the sample temperature after cryocooler deactivation to a rate on the order of 0.1 K per hour. The sample temperature is not constant; rather the sample and stabilizing mass are cooled below the maximum acceptable operating temperature before stopping the cryocooler. Then the entire cold mass warms gradually as vibration sensitive procedures (measurements) are performed. The cryocooler is restarted upon completion of the sensitive procedures, but before the cold mass has warmed past the maximum acceptable temperature. Finally, the cold mass is recooled in preparation for the next set of measurements.

Here, a design concept is proposed that may be used in fielding ICF targets at the National Ignition Facility (NIF). The targets contain 3-mm diameter deuterium-tritium spherical ice shells that must be imaged by an x-ray phase contrast system. The sample must be stable during imaging to within 1 micron for 2 minutes in order to capture an image with sufficient resolution. Additionally, the temperature of the surface that the sample is mounted to must be maintained at 7 K and stable to within 1 mK while providing 200 mW of cooling.

There are several aspects of NIF that specifically motivate the concept described below and restrict the use of more common approaches. To begin with, a liquid helium system cannot be used due to logistical difficulties of liquid helium handling at NIF. Secondly, geometric restrictions require the cold head to be mounted with the cold end axis horizontal, and thus prevent the use of a PT cooler. Finally, the cold head will be mounted to a remote cryostat that travels over a range of ~9.5 m relative to the compressor and other supporting equipment. It is desirable to minimize the number of cables and flex hoses that connect them.

The interest of minimizing system cost and complexity has led to a cryostat design involving a GM cryocooler with a stabilizing mass. Helium gas is used as the stabilizing mass. The use of helium preserves operational simplicity as a helium source is already part of GM (and PT) systems. No additional gas lines or sources are required to deliver gas to the cryostat. Additionally, helium is an excellent choice for stabilizing mass in terms of adding mass to the system because it has a higher heat capacity per volume in the temperature range of 4—10 K than most substances and therefore allows for a smaller temperature stabilizer volume.

Figure 1 illustrates a system that utilizes the cryocooler helium source for pressurizing the helium pot. Other configurations are possible. A similar helium pot system has been demonstrated for stabilizing temperature fluctuations associated with the GM cycle [4]. The density of the gas within the pot increases as the systems cools and gas is drawn into the pot from the cryocooler circuit. An additional helium tank and valving system (not shown) are likely to be required to replenish the gas in the cryocooler circuit. When the cryocooler is stopped, the helium pot gradually warms and helium is released back to the cryocooler circuit.

The pressure reducers maintain the helium pot at constant pressure to minimize temperature disturbances. Without the reducers or some other mechanism to prevent a sudden change in pressure, the pot pressure would shift abruptly when stopping or starting the cryocooler. The mass transfer and work associated with the pressure change would be accompanied by an abrupt temperature shift. Constant helium pot pressure requires that the pressure fall between the compressor's supply-side operating pressure and the stopped cryocooler circuit pressure. The pot can then be charged to a pressure that is obtainable by the compressor during its operation, and exhaust gas can reenter the cryocooler system's helium circuit as the helium pot warms when the cryocooler is off.

Constant sample temperature is a second requirement for fielding ICF targets. Pressurizing the helium above its critical pressure (227 kPa) implies that there is no phase change with an associated latent heat that will permit the stabilizing mass temperature to
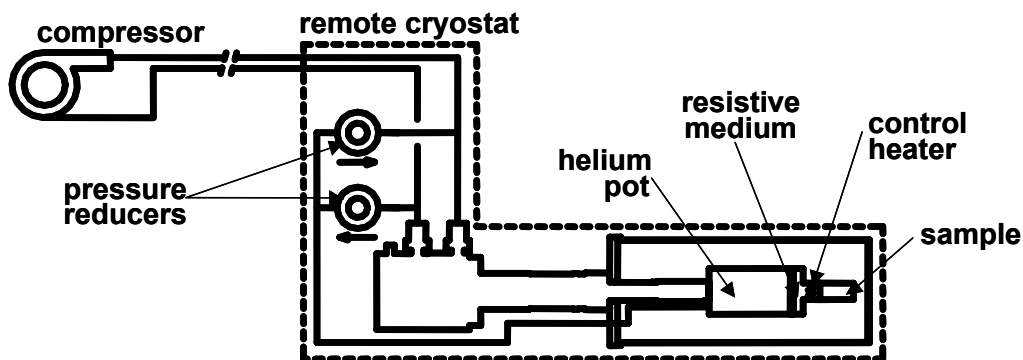
FIGURE 1. System that utilizes the cryocooler helium source to pressurize the helium pot.

remain constant as it absorbs heat. The pot will warm gradually once the cryocooler has been stopped. The sample temperature is stabilized using an active temperature control heater and a resistive medium that allows a temperature difference between the controlled temperature and the helium pot temperature, as indicated in the figure. The drawback to this method is the additional load from the control heater necessitating a larger volume for providing a specific hold time. However, the increased volume may be inconsequential as is the case with the ICF target cryostat.

Liquid helium could reduce the required stabilizer volume as a result of both a greater available cooling per volume and a substantial reduction in the control heat which is no longer required for offsetting the rising stabilizer temperature. Yet the autonomy and simplicity afforded by use of the cryocooler's helium source to charge the helium pot may not be realized with a liquid system due to the need for the helium to vent from the pot at a pressure that is considerably lower than the typical pressures of a GM cryocooler circuit.

A proof-of-concept system has been built to demonstrate intermittent operation of the cryocooler while maintaining the sample temperature constant. The proof-of concept system is simplified by charging the helium pot with a separate helium source from the cryocooler compressor unit. The helium pot is pressurized to a pressure that is typical for GM cryocooler gas lines when the cryocooler is off. A mathematical model for predicting the helium pot warming trend is verified using this experimental system. The model is then used to predict the relation among hold time, volume, operating temperatures, and heat leak.

PROOF-OF-CONCEPT SYSTEM

Figure 2 illustrates an overall layout of the proof-of-concept system. A "cold extension" that includes the helium pot, resistive medium, and a controlled temperature sample mount is hard-mounted to the second stage of a GM cryocooler that is rated to provide 200 mW of cooling at 4.2 K. A copper adaptor for mounting the sample is attached to the end of the helium pot opposite the cryocooler. The sample mount is separated from the helium pot by a stack of 2 brass plates, each 1 mm thick. The brass plates serve as the resistive medium that allows the sample mount temperature to be adjusted independent of the helium pot temperature. The cold extension has an overall length of 282 mm and an outer diameter of 67 mm. A 25-mm OD rod is attached to the sample mount to act as a "surrogate" sample.

The orientation and geometry of the cryocooler and cold extension were chosen to be compatible with the target characterization system that will implement this concept. The geometric limitations of this application require that the cryocooler and the cold extension be axially aligned and horizontal, as well as limit the helium pot diameter. The helium pot length was selected for providing the desired hold time.

The helium pot consists of a 190 mm long OFHC copper tube. The cylinder provides a conduction path across the helium pot to carry heat from the sample mount to the cryocooler 2nd stage heat station as well as a structure for containing the helium gas. The ends of the tube are capped and sealed by with copper discs that were joined to the tube using electron beam welding. 61 OFHC copper tubes extend from each end cap into the helium pot to enhance heat exchange between the helium gas and the helium pot structure. The majority of these tubes have an OD of 4.8 mm and an ID of 3.14 mm, providing helium fraction over the cross-section of the helium pot of 0.68. The internal volume of the helium pot is 436 ml.
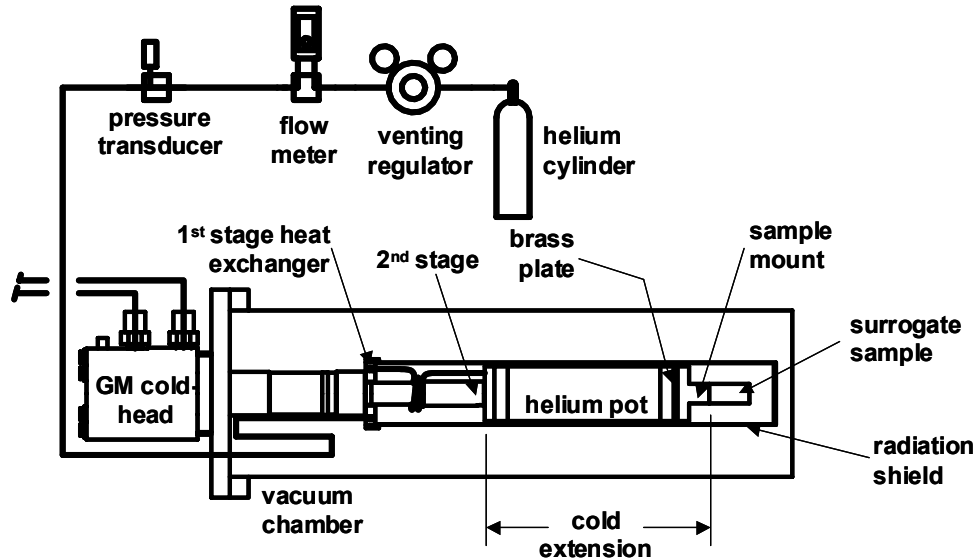
FIGURE 2. Schematic of the proof-of-concept system.

The radiation heat leak to the components mounted off the cryocooler 2nd stage is made negligible by enclosing within a copper radiation shield that is attached to the cryocooler 1st stage. 4 layers of single-aluminized mylar sheet is wrapped around the 2nd stage and the cold extension to further reduce radiation heat transfer. 20 layers were applied to the outer surface of the cryocooler 1st stage and the radiation shield.

Helium gas is supplied to the helium pot from a gas cylinder via a gas transfer system that includes several components joined by stainless steel tubing. The pressure is controlled with a venting regulator. The portion of the gas transfer system located outside the vacuum chamber includes a mass flow meter, a pressure transducer, and several operational and safety valves (not shown).

Inside the vacuum chamber, the gas passes through a heat exchanger that is mounted to the cryocooler 1st stage. The heat exchanger is essentially an OFHC copper disc that includes a narrow channel that the helium passes through as it travels to/from the helium pot. The channel length and cross-section are sized such that, for the expected entrance temperatures and flow rates, the gas temperature is brought within a few degrees of the 1st stage temperature before exiting the heat exchanger. Therefore, the more powerful 1st stage removes most of the enthalpy in the helium as it is cooled from room-temperature to the helium pot temperature, speeding the rate of cooldown and helium transfer to the helium pot. 3.2 mm OD stainless steel tubing provides passage between a vacuum chamber port and the helium pot. The tubing includes two sections. The first section runs parallel to the cryocooler from the room-temperature end to a gas port of the 1st stage heat exchanger. The second section connects the opposite port of the 1st stage heat exchanger to the helium pot. The tubing spirals around the cryocooler's 2nd stage to provide compliance between the ends.

Film heaters are mounted at 3 locations: (1) the sample mount for maintaining a constant temperature, (2) the sample for simulating a thermal load, and (3) on the cryocooler's 2nd stage to allow adjustment of the entire cold extension temperature. Temperatures are measured at 5 locations, including: 1) the cryocooler 1st stage, 2) the cryocooler 2nd stage, 3) & 4) both ends of the helium pot, and 5) the sample mount. The helium pot and sample mount temperatures

are measured using calibrated Cernox sensors with rated accuracy of ±5 mK, while the remaining temperatures are silicon diodes with ±0.25 K accuracy.

The sample mount temperature is controlled with a PID controller. The controller reads the sample mount temperature sensor and modulates a power supply that powers the sample mount heater. The remaining sensors are excited using separate constant current sources. A data acquisition system records all sensor voltages, the sample mount heater voltage, and the flow meter output. A multi-channel power supply drives the remaining heaters.

SYSTEM OPERATION

A set of temperature measurements are performed to determine the thermal resistance across the brass plates when the sample mount is maintained at 7 K. The helium pot temperature is adjusted using the 2nd stage heater while the cryocooler operates continuously. The resistance is derived from the difference between the sample mount temperature and the helium pot temperature at the sample end, and the heat load applied by the sample mount heater. Measurements are performed for several helium pot temperatures (4—6.5 K) and sample heat loads (0—300 mW). The resistance varies roughly linearly with temperature from 12.5 K/W at 4 K to 8.5 K/W at 6.5 K. The contribution to this resistance by the copper separating the sensors from the brass plates is expected to be negligible.

Intermittent cryocooler operation with constant sample mount temperature is demonstrated after cooling from room-temperature with the helium pot pressurized to 1.55 MPa. Figure 3 shows the temperature and flow response during the cooldown. As the helium pot cools, the gas it contains under constant pressure will increase in density and helium is drawn in. The helium flow rate rises sharply after 7 hr because, at lower temperature, both the helium pot cooldown rate accelerates and the helium density varies faster with temperature. The 1st stage temperature rises in response to the increased rate of heat rejection by the faster helium flow that enters the heat exchanger at room-temperature. The helium flow rate drops off to zero as the temperatures, and consequently the helium density within the pot, approach
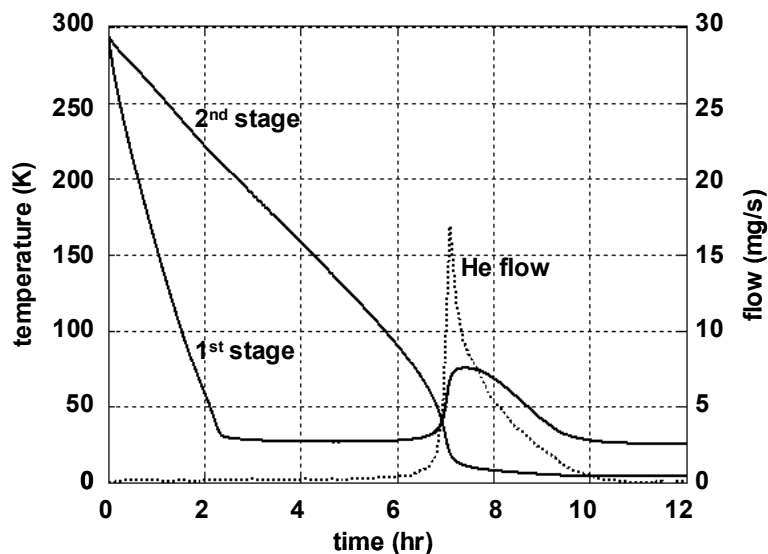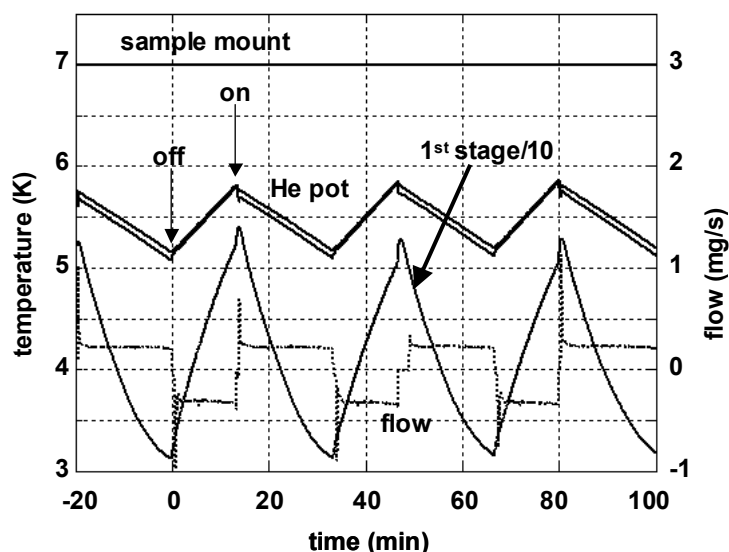

FIGURE 3. Cooldown trend with a helium pot pressure of 1.55 MPa.

FIGURE 4. Temperature and flow response when cycling the cryocooler state.

steady-state at 3.5 K.

After the system has reached steady-state following cooldown, intermittent operation is demonstrated by stopping and restarting the cryocooler several times. Figure 4 shows the temperature response resulting when cycling the cryocooler on and off, with a duty cycle of 800 s off and 1200 s on. The sample mount temperature is maintained at 7 K while the dummy sample dissipates 103 mW. As the helium pot warms when the cryocooler is off, the gas within it expands and the venting regulator allows helium to vent (indicated by a negative flow rate in the figure). The helium flow switches direction to refill the pot when the cryocooler is restarted and the helium pot is recooled.

The warming/recooling trends shown in the plot follow a long series of cycles with different minimum and maximum helium pot temperature. The minimum and maximum temperature reach steady values after a sufficient number of cycles. If the first warming trend starts with a temperature that is cooler than the minimum temperature observed after many cycles, then the minimum and maximum temperatures gradually shift upwards with each successive cycle. When the helium pot operates within a warmer temperature range, the temperature drop across the brass plates is smaller and therefore the sample mount heater dissipates less heat to impose this temperature drop. However, more cryocooler cooling is provided during the operational phase because the cryocooler performance improves as temperature is increased. The steady minimum and maximum temperature values fall where there is a balance between the heat that must be absorbed during the stopped phase and the heat that is removed during the operational phase.

The temperature and gas flow response following cryocooler deactivation without any temperature control heating was also recorded several times. As before, all temperatures were permitted to reach steady state prior to deactivation. The measured response, shown in Figure 5, is used to estimate the total heat leak to the cold extension as a function of the 1st stage temperature when the cryocooler is off. Derivation of this function and its application to the warming trend prediction for the cryocooler cycling with controlled sample temperature is discussed below.
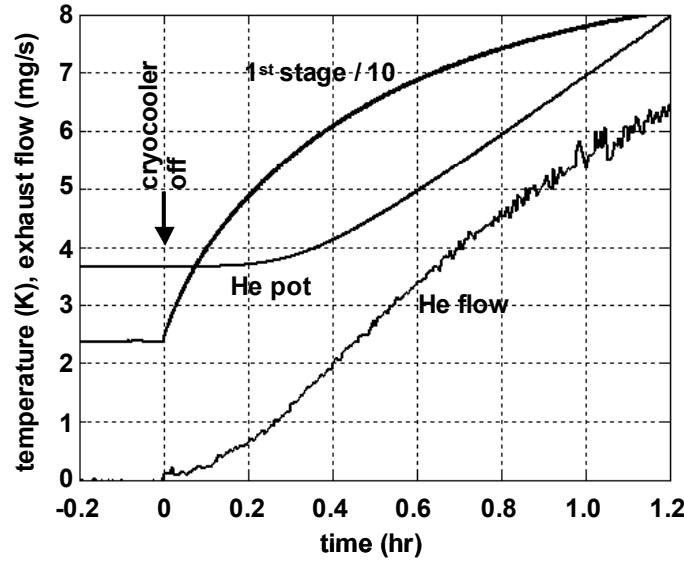
FIGURE 5: Temperature and flow response with no heater loads.

THERMAL MODEL

A simple model representing the cold extension is illustrated by the thermal circuit of Figure 6. The helium pot is represented by a fixed volume V from which mass may exit. The gas within the volume is assumed to have uniform temperature T_{He}, which is the case as long as the helium pot's internal copper tubes have been sized and spaced to maintain negligible temperature gradients within the helium.

The sample mount is fixed at temperature T_M as enforced by the temperature control system and is separated from the helium volume by the temperature-dependent resistance, R, across the brass plates. Heat loads imparted on the sample mount include dissipation from the sample Q_S and the control heater Q_C. A third heat load Q_L flows directly into the helium volume and represents the combination of various heat leak sources. Significant sources include heat conduction through the cryocooler when it is stopped, and heat conduction along the electrical leads and the gas line.

Heat capacities of all materials other than the helium is assumed negligible. With the exception of the cryocooler, the remaining cold components are almost entirely copper and occupy roughly the same amount of volume in the cold extension as the helium, but have heat capacity per volume that is less than 1/200th that of helium at temperatures below 7 K. The

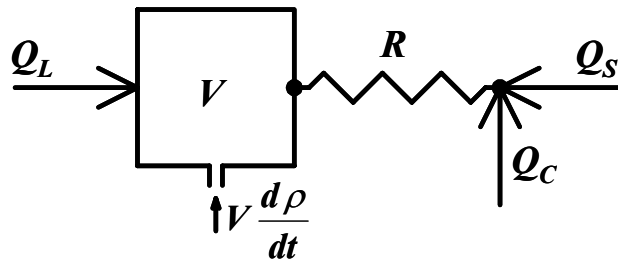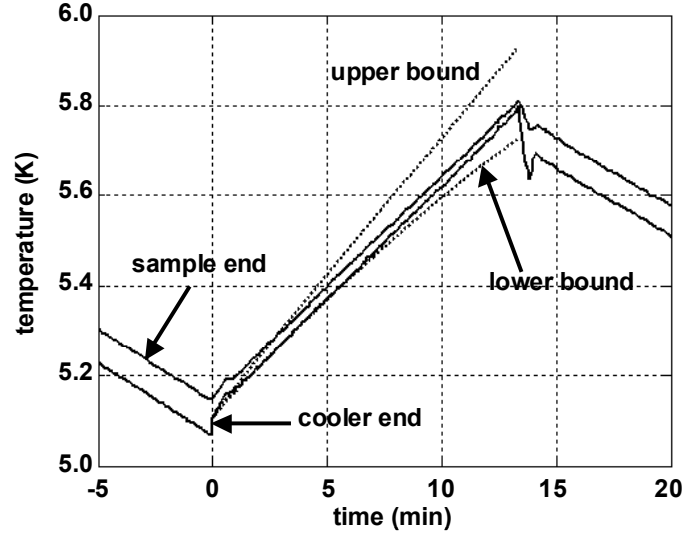**FIGURE 6**. Model for estimating the helium pot warming trend.

FIGURE 7. Calculated bounds for the helium pot warming trend.

cryocooler's 2nd stage may contribute significant heat capacity for its size, but is much smaller than the cold extension.

The following equation is derived by applying the first law for an open system:

$$\frac{dT_{He}}{dt} = \frac{Q_L + Q_S + Q_C(T_{He})}{V\left[\rho(T_{He})c_v(T_{He}) - \frac{P}{\rho(T_{He})}\frac{d\rho(T_{He})}{dT_{He}}\right]}$$ (1)

where P is the helium pressure, ρ is density, and c_v is the specific heat. This equation is first applied to the warming trend of Figure 6 with zero Q_S and Q_C to predict Q_L as a function of 1st stage temperature, T_1. Q_L is solved for and the measured T_{He} and dT_{He}/dt are applied to a numerical calculation over a range of recorded time steps. The calculated Q_L as a function of time is then matched to the recorded T_1, leading to Q_L as a function of T_1. Q_L varies from value 30 mW at 30 K to 300 mW at 80 K.

Equation 1 is also used to simulate the helium pot's warming trend. dT_{He} is solved for and integrated using a finite-difference method with Q_S set equal to the experimental value and Q_C is calculated by the relation that provides a constant T_M:

$$Q_C = \frac{T_M - T_{He}}{R(T_{He})} - Q_S$$ (2)

while applying the $R(T_{He})$ that was measured as described in the experimental section. The warming trend prediction is first performed with Q_L as calculated above. Then the prediction is repeated with Q_L set to zero. It is suspected that the heat leak through the cryocooler is a function of time as well as temperature, as would be expected if thermal diffusion is not rapid in comparison to the time span over which the cryocooler does not operate. If this is the case, then neither calculation will exactly correspond to the measured warming trend; but the two

calculations should bound the measurement shown in Figure 7 where the actual warming trend for a single cycle is shown with the calculated bounds. It appears that Q_L is actually negligible over the first ~7 minutes of warming.


PARAMETRIC ANALYSIS

Duty cycle (hold time / recooling time), hold time, and volume are the attributes most likely to be of interest when assessing the use of this system in a particular application. This analysis is limited to the prediction of hold time and volume as recooling time is mostly dependent on the cryocooler. The model demonstrated above is applied to a range of sample load, sample temperature, and initial helium pot temperature. The relationship between hold time per volume of helium, τ/V_{He}, is determined as a function of these parameters.

Throughout this analysis the heat leak term is neglected, as was determined to be appropriate for hold times on the order of minutes with the experimental apparatus. The analysis is further simplified by maintaining R constant. Hold time per volume can then be calculated by rearranging Equation 1 and integrating:

$$\frac{\tau}{V} = \int_{T_0}^{T_M - Q_S R} \frac{\left[\rho(T_{He})c_v(T_{He}) - \dfrac{P}{\rho(T_{He})}\dfrac{d\rho(T_{He})}{dT_{He}} \right]}{Q_L + \dfrac{T_M - T_{He}}{R(T_{He})}} dT_{He} \tag{3}$$

where T_0 is the helium pot temperature when the cryocooler is stopped. The helium pot is
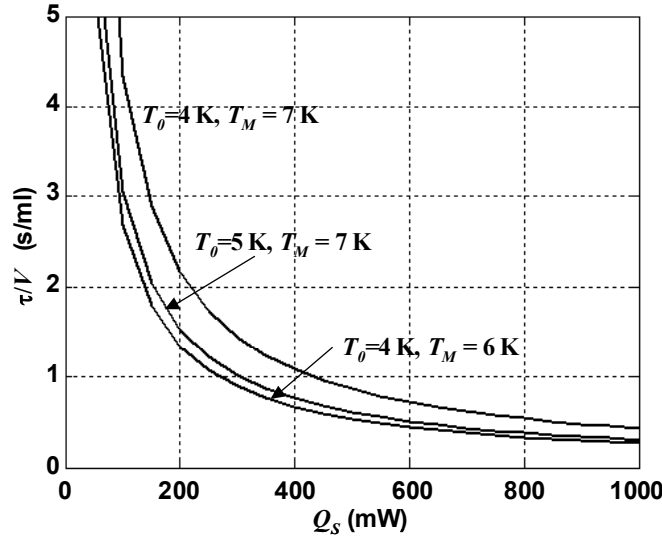
FIGURE 8. Predicted hold time per helium volume plotted against sample heat load for various sample temperatures and initial helium temperature.

allowed to warm until the control heat has reduced to zero, at which point the helium pot temperature is given by $T_M - Q_S R$, which is the upper integration limit in Equation 3. An appropriate value for R must be selected in order to evaluate the right-hand-side integral. The hold time is increased by increasing the maximum helium pot temperature, which implies a smaller R. At the same time, the hold time may also be increased by decreasing dissipation in the control heater, which implies a larger R. Therefore there is an optimum value of R for maximizing hold time for a particular set of operating temperatures and load.

A numerical code was constructed to calculate Equation 3 for a specific set of T_M, T_0, and Q_S over a range of R until the optimum value is found. Figure 7 shows the results of this code plotted as several τ / V_{He} versus Q_S curves, each representing a different set of T_M and T_0.. The plots indicate that with a sample load of several hundred milliwatts, hold times on the order of minutes may be achieved with fairly modest helium volumes (100s of ml) when considering the size of a typical GM cryocooler cold-head.

CONCLUSIONS

The addition of a helium pot to a cryocooler system allows for deactivation of the cryocooler and the elimination of a significant vibration source. Such a scheme may be useful for vibration sensitive procedures with limited duration. The helium pot design may be a simpler and less expensive alternative to other low vibration cryocooler designs, and does not require any additional connections between the compressor unit and the cryostat. Experimental and theoretical predictions indicate that modest helium pot volumes (hundreds of milliliters) allow for the cold sample to be maintained at ~7 K for hold times of up to 1 hr can be achieved for samples with negligible heat dissipation, or several minutes for samples with hundreds of milliwatts of dissipation.

ACKNOWLEDGEMENTS

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